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International application number: PCT/IL05/000132

International filing date: 03 February 2005 (03.02.2005)

Document type: Certified copy of priority document

Document details: Country/Office: US
Number: 60/541,256
Filing date: 04 February 2004 (04.02.2004)

Date of receipt at the International Bureau: 31 May 2005 (31.05.2005)

Remark: Priority document submitted or transmitted to the International Bureau in compliance with Rule 17.1(a) or (b)

World Intellectual Property Organization (WIPO) - Geneva, Switzerland
Organisation Mondiale de la Propriété Intellectuelle (OMPI) - Genève, Suisse

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APPLICATION NUMBER: ***60/541,256***
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This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

Express Mail Label No.

INVENTOR(S)

Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
MOSHE	SHOHAM	HOSHAYA, ISRAEL

Additional inventors are being named on the ✓ separately numbered sheets attached hereto

TITLE OF THE INVENTION (500 characters max)

A SINGLE SENSOR FOR VERIFICATION OF PARALLEL ROBOT LOCATION

Direct all correspondence to: **CORRESPONDENCE ADDRESS**

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OR

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ENCLOSED APPLICATION PARTS (check all that apply)

☒ Specification Number of Pages 4 ☐ CD(s), Number

☐ Drawing(s) Number of Sheets ☐ Other (specify)

☐ Application Date Sheet. See 37 CFR 1.76

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Respectfully submitted,

SIGNATURE Moshe Shoham

TYPED or PRINTED NAME Moshe Shoham

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Date 2/2/2004

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01-Feb-04

A Single Sensor for Verification of Parallel Robot Location

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1. Introduction

Robotic systems have been recently entered the medical arena for enhancing the surgeons' ability in precise and minimally invasive positioning of surgical tools. In particular, they have been used for remote manipulation (e.g. Intuitive Surgical's Davinci) as semi active devices for brain biopsies applications (e.g. Cyberknife and Neuromate) and as an active robot for hip and knee replacement (e.g. ISS's Robodoc). In order to increase the system reliability in these hazardous tasks these robots have been equipped with a double set of encoders (position sensors) that measure the actual joint motions and provide the input for an algorithm that determines the surgical tool position and orientation. Double set of sensors is used to serve as a backup for the case of an encoder (sensor) failure.

In serial type robot where the links and joints are connected in series, each joint actuator affects the end-effector location and there is no internal position sensor that measures the end-effector location. Hence each encoder is backed up by a second encoder on the same axis.

In a parallel type robot it is possible to measure the end-effector location directly relative to the base and hence to locate the second set of sensors not necessarily at the joints but rather between the base and the output.

In an earlier disclosure [1] it was suggested that for a six DOF parallel robot only three encoders are sufficient to provide the backup for sensor failure.

In the present disclosure it is shown that for any statistical significance result it is possible to used only one extra sensor (encoder) in order to provide the necessary backup for encoder failure in robots.

As an example consider a parallel robot with six extensible links as shown in Fig. 1, (It should be mentioned that the exact same analysis applies also to other parallel robots). The six extensible links are connected between the base and the moving platform with spherical joint at one side of the link and U joints at the other. In addition, each link length is measured by a position sensor (encoder) that moves with the link.

2. Adding one extra sensor for verification of the moving platform location

One extra sensor- namely the 7^{th} sensor (see Fig. 2) - is now added and measures the distance between the moving and the base platforms centers. Changing the extensible link lengths generally changes the distance between the platforms' centers and hence is detected by the 7^{th} sensor. Since the moving platform to which the 7^{th} sensor is connected, is a rigid body the length of the sensor is uniquely determined by the length of the six links and hence provides a backup for the case of incorrect platform position.

The main question is does this single sensor can detect any unwanted platform motion in case the link length's sensors have failed?

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This theoretically might happen. For example if all the six link length sensors fail and are off by the same amount then the moving platform changes its orientation while keeping its center fix and hence keeping fix the length and the measurement of the 7^{th} sensor.
Similarly, if three of the actuators fail and the other symmetrical three fail the same amount to the other direction then the moving platform might perform a pure rotation which is not detected by the 7^{th} position sensor.

Our problem is to find how likely these cases, where there are combinations of sensor failures that are neither detected by the joint control system nor by the 7^{th} sensor, might happen.

3. Analysis of the 7^{th} sensor detection capability

3.1 Failure of one sensor

Let's start the analysis with a failure of one link-length sensor.
Failing of one sensor means that the actuator moves changing its link length while closing the erroneous position signal generated by the fault sensor.

The question is what the cases are where this error is not detected by the 7^{th} sensor.

In order to identify these problematic cases the moving platform trajectories that maintain constant the 7^{th} sensor reading should be calculated.

In some cases the moving platform is displaced while all the actuators maintain their length. This is called a singular configuration in which the moving platforms gains an extra degree-of-freedom. Most robots as well as the application considered here are designed in such a way that all the singular configurations are out of its work envelope.
However, when one sensor fails there are still 6 known measured distances between the platforms, namely 5 link-length sensors and the 7^{th} sensor. This constitutes a "new" robot where the 6 link lengths are measured at different locations at the platforms than the original robot one. If this "new" robot contains singular configurations within the original robot work volume it means that the moving platform is able to move without being detected by the 7^{th} sensor and the backup system fails.
If no singular configurations exist with the robot work volume then any unwanted motion generated by an erroneous link-length sensor it detected by the 7th sensor. This is true since otherwise we have for the same position and orientation of the moving platform (determined up to a single assembly mode by the inverse kinematics from the 5 link-length sensors and the 7^{th} sensor) two different distinct solutions for the link lengths.

To determine what the singular configurations of the "new" robot are it is required either to conduct an analytical analysis, e.g. [2,3,4] or to search the entire workspace of the manipulator.

Assuming that such singular configurations do not exist within the robot workspace, the conclusion is that there is no possible motion of the robot that can go undetected by the 7th sensor if only one encoder fails.

3.2 Failure of two sensors

Consider now that two sensors are simultaneously incorrect.

The likelihood of this case is quite low. Moreover, even if two sensors fails at the same time and give erroneous readings, this also is detected by the 7th sensor unless the values given by the two failed sensors are in such a proportion that matches a valid displacement of the moving platform.

In particular, when the location of the moving platform is defined by only 5 distance readings (4 link-lengths and the 7th sensor), then it is not fully defined and the platform might moves freely and have infinite number locations.

Now whatever the reading of one failed sensor is it "locks" the moving platform since we are again at the previous case with only one failing sensor. It means that there is only one combination (within the current assembly mode) of the two failing sensors that match the rest 5 correctly operated sensors.

Based on this analysis the probability that the platform moves without being detected by the 7th sensor when one or two sensors simultaneously fail is calculated as follows:

1. Make sure that there is no singular points of a robot composed of 5 link-length sensors and the 7th sensor within the entire robot workspace.
2. In this case find the probability that one sensor may fail.
3. The probability that both failed simultaneously is the square of the probability that one fails.
4. The probability two fail simultaneously and give valid reading is the square of the probability one fails times the reciprocal of the number of increments (resolution) in one sensor.

4. Example: SpineAssist (Mazor Surgical Technology)

In the case of Mazor's SpineAssiste robot the probability of one sensor to fail during an operation that lasts an hour while the sensor life time is 10,000 hours, is 10^{-4}. The sensor resolution is 12 bit = 4096. Hence the probability for a mistaken motion not detected by the 7th sensor due to two failed sensors is $10^{-4}*10^{-4}*4096^{-1} = 2.44*10^{-12}$ The lifetime of each robot is planned to be 500 hours; hence the probability for undetected platform motion during the robot lifetime is $\underline{1.22*10^{-9}}$.

Taking into consideration that the sensor reading is affected also by other factors like ADC, LVDT card and power supply the probability for an error reading during one surgery might be reduced to10^{-3}. Hence the probability for a mistaken motion not detected by the 7th sensor due to two failed sensors is $10^{-3}*10^{-3}*4096^{-1} = 2.44*10^{-10}$, and during the robot lifetime of 500 hours is $\underline{1.22*10^{-7}}$. Noting that each robot is planned to performs 500 surgeries this accumulated to one error per the entire population on earth.

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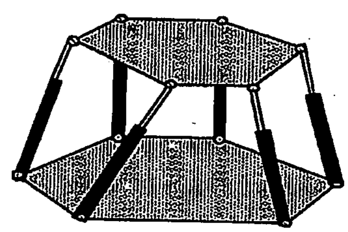

Figure 1: A six extensible links parallel robot

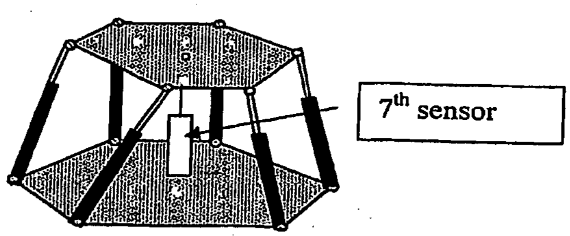

Figure 2: A six extensible links parallel robot with one redundant 7th sensor